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THE EAR

by Georg von Békésy

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THE EAR

It translates sound between some 16 cycles per second and 20,000 into nerve impulses. Together with the auditory centers of the brain, it is an instrument that is not only remarkably sensitive but also selective

by Georg von Békésy

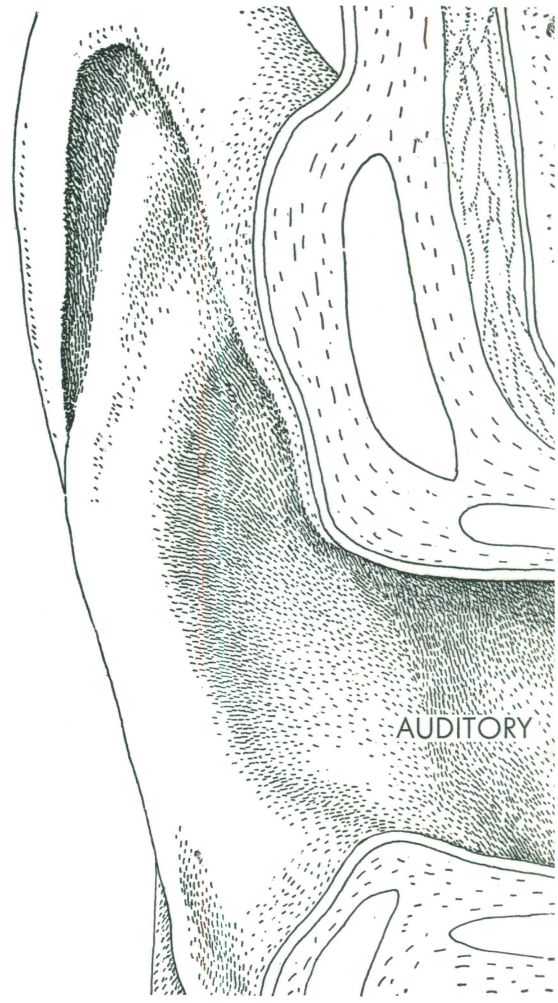
Even in our era of technological wonders, the performances of our most amazing machines are still put in the shade by the sense organs of the human body. Consider the accomplishments of the ear. It is so sensitive that it can almost hear the random rain of air molecules bouncing against the eardrum. Yet in spite of its extraordinary sensitivity the ear can withstand the pounding of sound waves strong enough to set the body vibrating. The ear is equipped, moreover, with a truly impressive selectivity. In a room crowded with people talking, it can suppress most of the noise and concentrate on one speaker. From the blended sounds of a symphony orchestra the ear of the conductor can single out the one instrument that is not performing to his satisfaction.

In structure and in operation the ear is extraordinarily delicate. One measure of its fineness is the tiny vibrations to which it will respond. At some sound frequencies the vibrations of the eardrum are as small as one billionth of a centimeter—about one tenth the diameter of the hydrogen atom! And the vibrations of the very fine membrane in the inner ear which transmits this stimulation to the auditory nerve are nearly 100 times smaller in amplitude. This fact alone is enough to explain why hearing has so long been one of the mysteries of physiology. Even today we do not know how these minute vibrations stimulate the nerve endings. But thanks to refined electro-acoustical instruments we do know quite a bit now about how the ear functions.

What are the ear's abilities? We can get a quick picture of the working condition of an ear by taking an audiogram, which is a measure of the threshold of hearing at the various sound frequencies. The hearing is tested with pure tones at various frequencies, and the audiogram tells how much sound pressure on the eardrum (*i.e.*, what intensity of sound) is necessary for the sound at each frequency to be just barely audible. Curiously, the audiogram curve often is very much the same for the various members of a family; possibly this is connected in some way with the similarity in the shape of the face.

The ear is least sensitive at the low frequencies: for instance, its sensitivity for a tone of 100 cycles per second is 1,000 times lower than for one at 1,000 cycles per second. This comparative insensitivity to the slower vibrations is an obvious physical necessity, because otherwise we would hear all the vibrations of our own bodies. If you stick a finger in each ear, closing it to air-borne sounds, you hear a very low, irregular tone, produced by the contractions of the muscles of the arm and finger. It is interesting that the ear is just insensitive enough to low frequencies to avoid the disturbing effect of the noises produced by muscles, bodily movements, etc. If it were any more sensitive to these frequencies than it is, we would even hear the vibrations of the head that are produced by the shock of every step we take when walking.

On the high-frequency side the range that the ear covers is remarkable. In childhood some of us can hear well at frequencies as high as 40,000 cycles per second. But with age our acuteness of hearing in the high-frequency range steadily falls. Normally the drop is almost as regular as clockwork: testing several persons in their 40s with tones at a fixed level of intensity, we found that over a period of five years their upper limit dropped about 80 cycles per second every six months. (The experiment was quite depressing to most of the participants.) The aging of the ear is not difficult to understand if we assume that the elasticity of the tissues in the inner ear declines in the same way as that of the skin: it is well known that the skin becomes less resilient as we grow old—a



PARTS OF THE EAR are illustrated in somewhat simplified cross section. Be-

phenomenon anyone can test by lifting the skin on the back of his hand and measuring the time it takes to fall back.

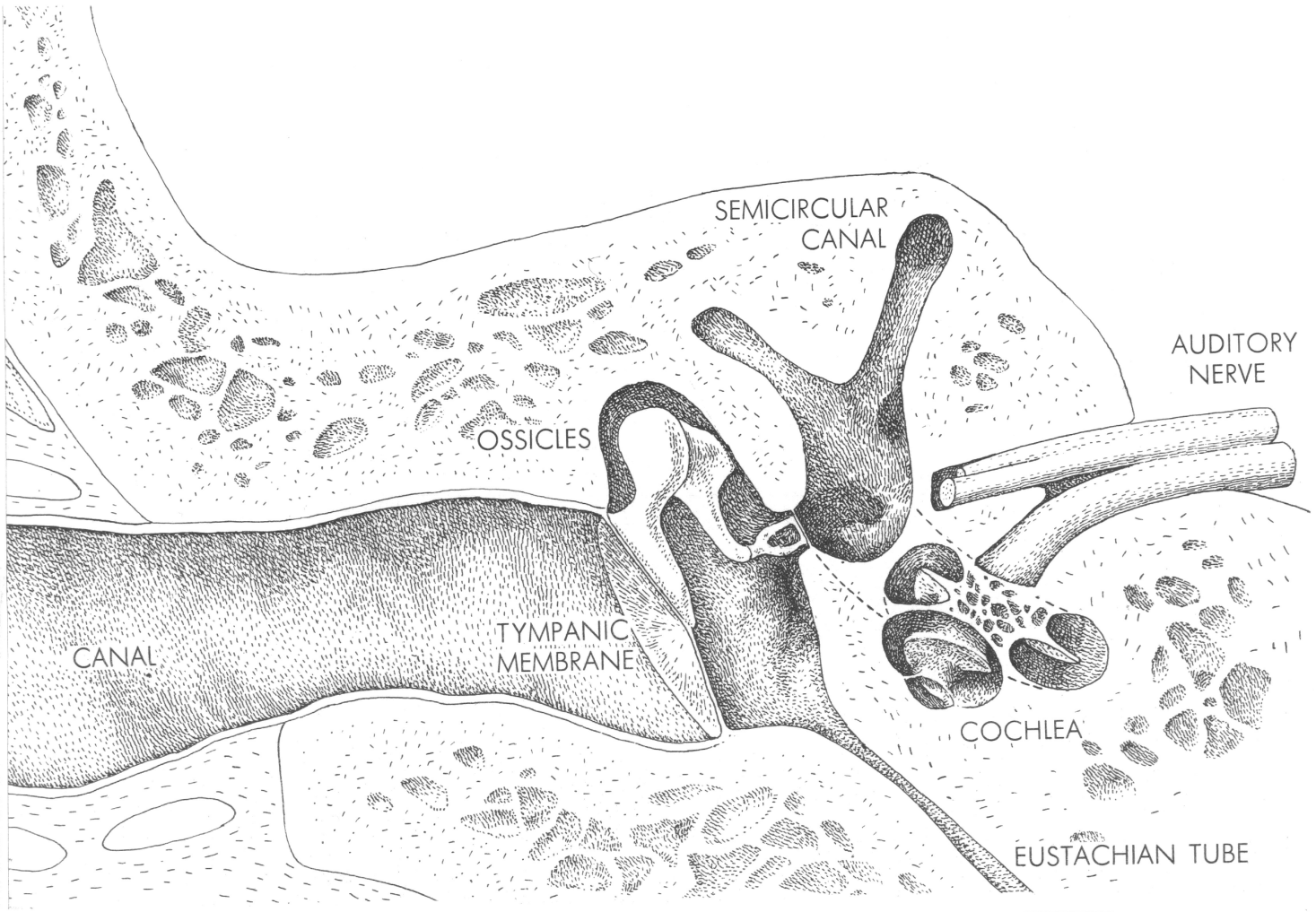
However, the loss of hearing sensitivity with age may also be due to nerve deterioration. Damage to the auditory nervous system by extremely loud noises, by drugs or by inflammation of the inner ear can impair hearing. Sometimes after such damage the hearing improves with time; sometimes (*e.g.*, when the damaging agent is streptomycin) the loss is permanent. Unfortunately a physician cannot predict the prospects for recovery of hearing loss, because they vary from person to person.

Psychological factors seem to be involved. Occasionally, especially after an ear operation, a patient appears to improve in hearing only to relapse after a short time. Some reports have even suggested that operating on one ear has improved the unoperated ear as well. Since such an interaction between the two ears would be of considerable neurological interest, I have investigated the matter, but I have never found an improvement in the untreated ear that could be validated by an objective test.

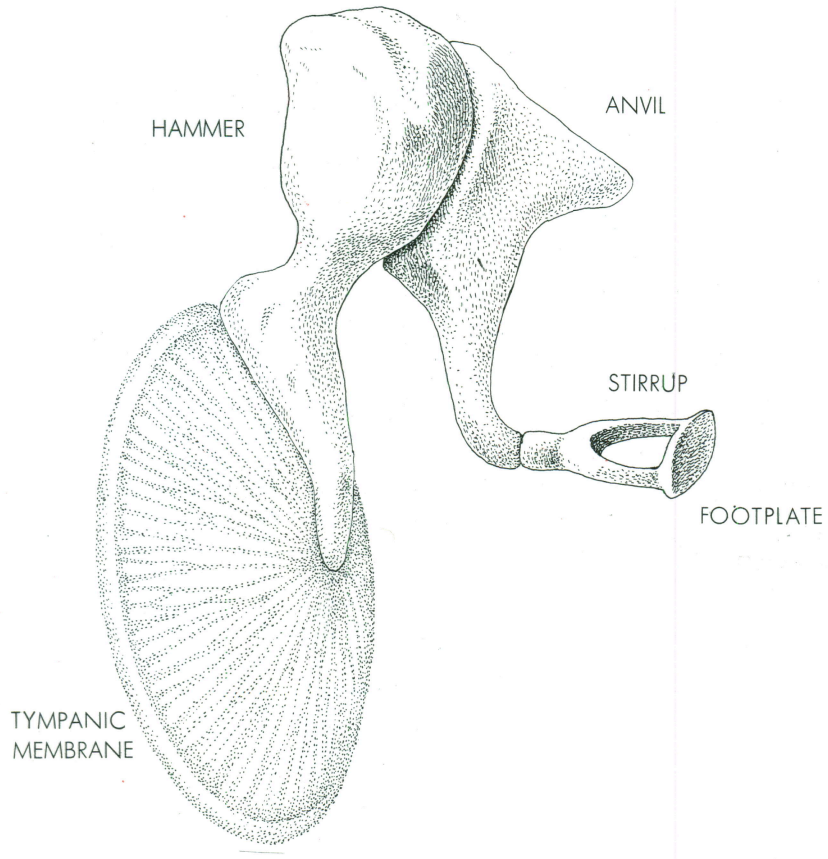
Structure of the Ear

To understand how the ear achieves its sensitivity, we must take a look at the anatomy of the middle and the inner ear. When sound waves start the eardrum (tympanic membrane) vibrating, the vibrations are transmitted via certain small bones (ossicles) to the fluid of the inner ear. One of the ossicles, the tiny stirrup (weighing only about 1.2 milligrams), acts on the fluid like a piston, driving it back and forth in the rhythm of the sound pressure. These movements of the fluid force into vibration a thin membrane, called the basilar membrane. The latter in turn finally transmits the stimulus to the organ of Corti, a complex structure which contains the endings of the auditory nerves. The question immediately comes up: Why is this long and complicated chain of transmission necessary?

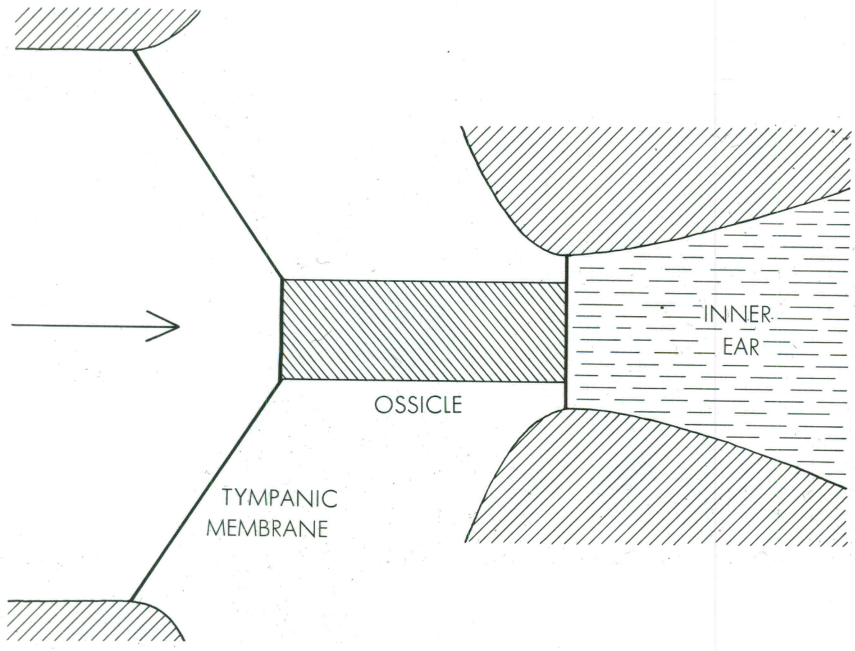
The reason is that we have a formidable mechanical problem if we are to extract the utmost energy from the sound waves striking the eardrum. Usually when a sound hits a solid surface, most of its energy is reflected away. The problem the ear has to solve is to absorb this energy. To do so it has to act as a kind of mechanical transformer, converting the large amplitude of the sound pressure waves in the air into more forceful vibrations of smaller amplitude. A hydraulic press is such a transformer: it multiplies the pressure acting on the surface of a piston by concentrating the force of the pressure upon a second piston of smaller area. The middle ear acts exactly like a hydraulic press: the tiny footplate of the stirrup transforms the small pressure on the surface of the eardrum into a 22-fold greater pressure on the fluid of the inner ear. In this way the



tween the eardrum (tympanic membrane) and the fluid-filled inner ear are the three small bones (ossicles) of the middle ear. The auditory nerve endings are in an organ (*not shown*) between the plate of bone which spirals up the cochlea and the outer wall of the cochlea.



THREE OSSICLES transmit the vibrations of the tympanic membrane to the inner ear. The footplate of stirrup, surrounded by a narrow membrane, presses against inner-ear fluid.



HOW OSSICLES ACT as a piston pressing against the fluid of the inner ear is indicated by this drawing. Pressure of the vibrations of tympanic membrane are amplified 22 times.

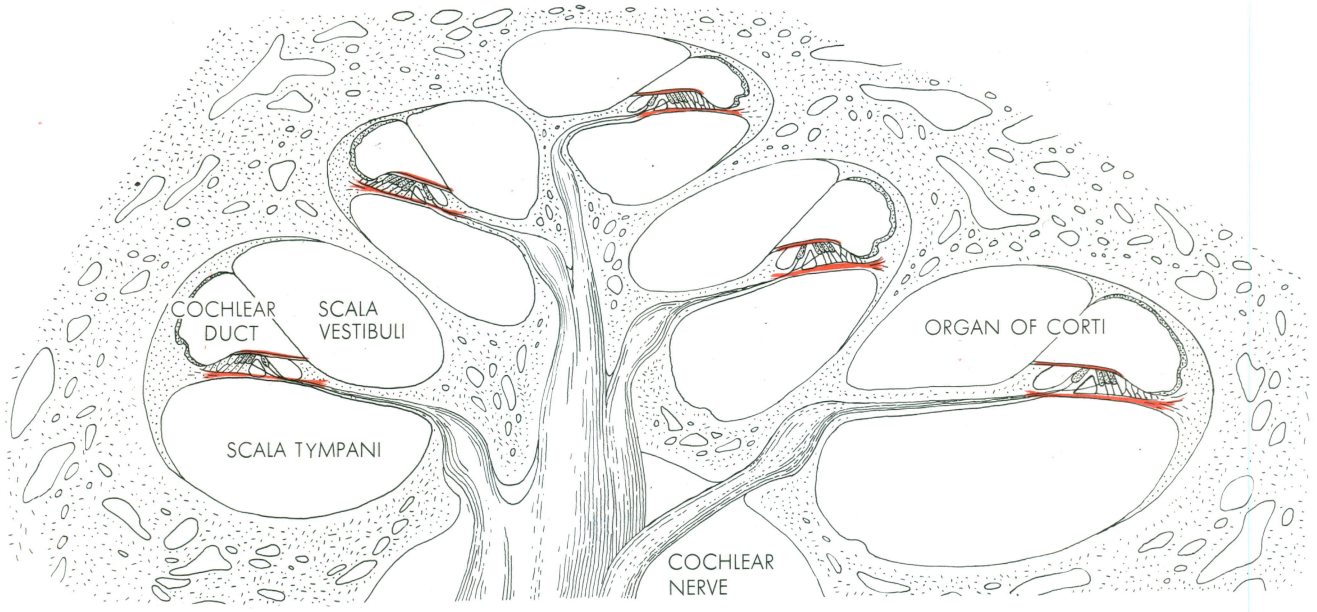
ear absorbs the greater part of the sound energy and transmits it to the inner ear without much loss.

But it needs another transformer to amplify the pressure of the fluid into a still larger force upon the tissues to which the nerves are attached. I think the ear's mechanism for this purpose is very ingenious indeed. It is based on the fact that a flat membrane, stretched to cover the opening of a tube, has a lateral tension along its surface. This tension can be increased tremendously if pressure is applied to one side of the membrane. And that is the function of the organ of Corti. It is constructed in such a way that pressure on the basilar membrane is transformed into shearing forces many times larger on the other side of the organ [*see diagram at bottom of opposite page*]. The enhanced shearing forces rub upon extremely sensitive cells attached to the nerve endings.

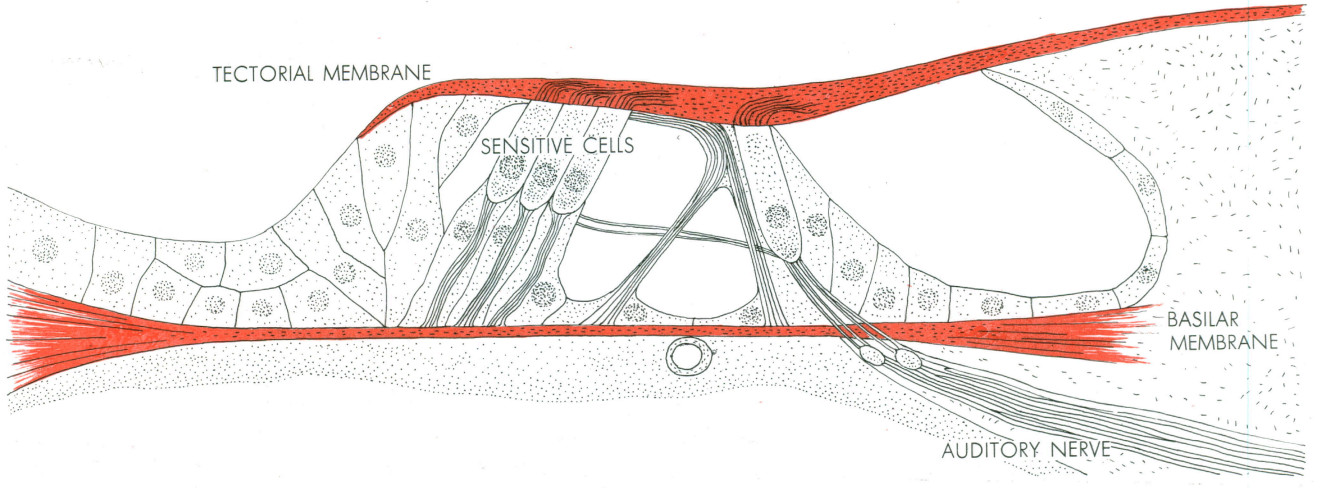
The eardrum is not by any means the only avenue through which we hear. We also hear through our skull, which is to say, by bone conduction. When we click our teeth or chew a cracker, the sounds come mainly by way of vibrations of the skull. Some of the vibrations are transmitted directly to the inner ear, by-passing the middle ear. This fact helps in the diagnosis of hearing difficulties. If a person can hear bone-conducted sounds but is comparatively deaf to air-borne sounds, we know that the trouble lies in the middle ear. But if he hears no sound by bone conduction, then his auditory nerves are gone, and there is no cure for his deafness. This is an old test, long used by deaf musicians. If a violin player cannot hear his violin even when he touches his teeth to the vibrating instrument, then he knows he suffers from nerve deafness, and there is no cure.

Speaking and Hearing

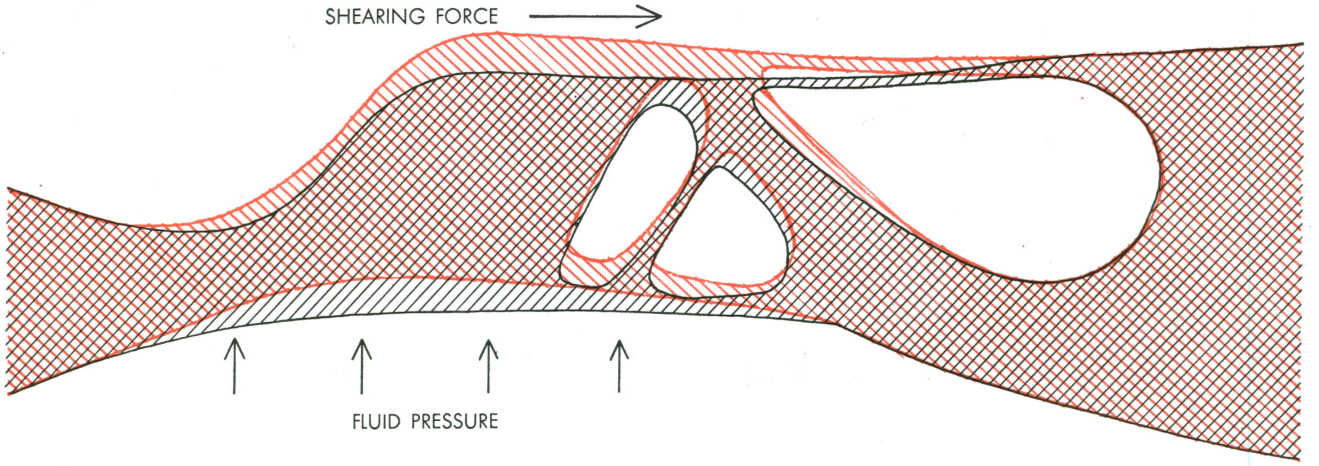
Hearing by bone conduction plays an important role in the process of speaking. The vibrations of our vocal cords not only produce sounds which go to our ears via the air but also cause the body to vibrate, and the vibration of the jawbone is transmitted to the ear canal. When you hum with closed lips, the sounds you hear are to a large degree heard by bone conduction. (If you stop your ears with your fingers, the hum sounds much louder.) During speaking and singing, therefore, you hear two different sounds—one by bone conduction and the other by air conduction. Of course another listener hears only the air-conducted sounds. In these sounds



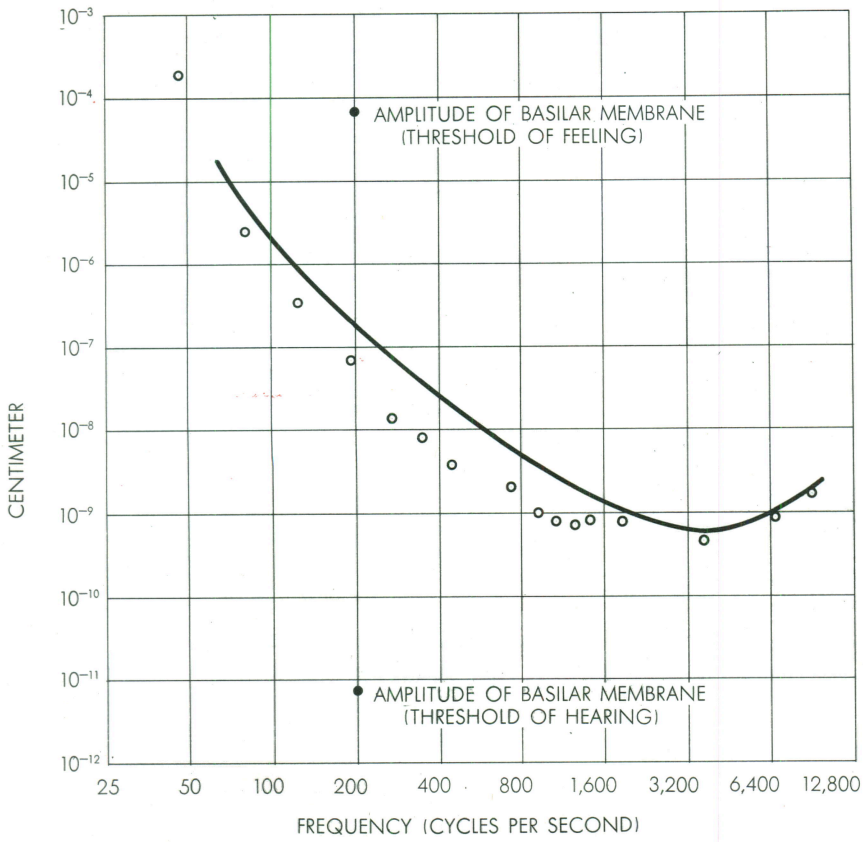
TUBE OF THE COCHLEA, coiled like the shell of a snail, is depicted in cross section. The plate of bone which appears in the cross section on pages 2 and 3 juts from the inside of the tube. Between it and the outside of the tube is the sensitive organ of Corti.



ORGAN OF CORTI lies between the basilar and tectorial membranes. Within it are sensitive cells which are attached to a branch of the auditory nerve (*lower right*). When fluid in scala tympani (*see drawing at top of page*) vibrates, these cells are stimulated.



HOW VIBRATION FORCES ARE AMPLIFIED by the organ of fluid in the scala tympani exerts a force on the basilar membrane,



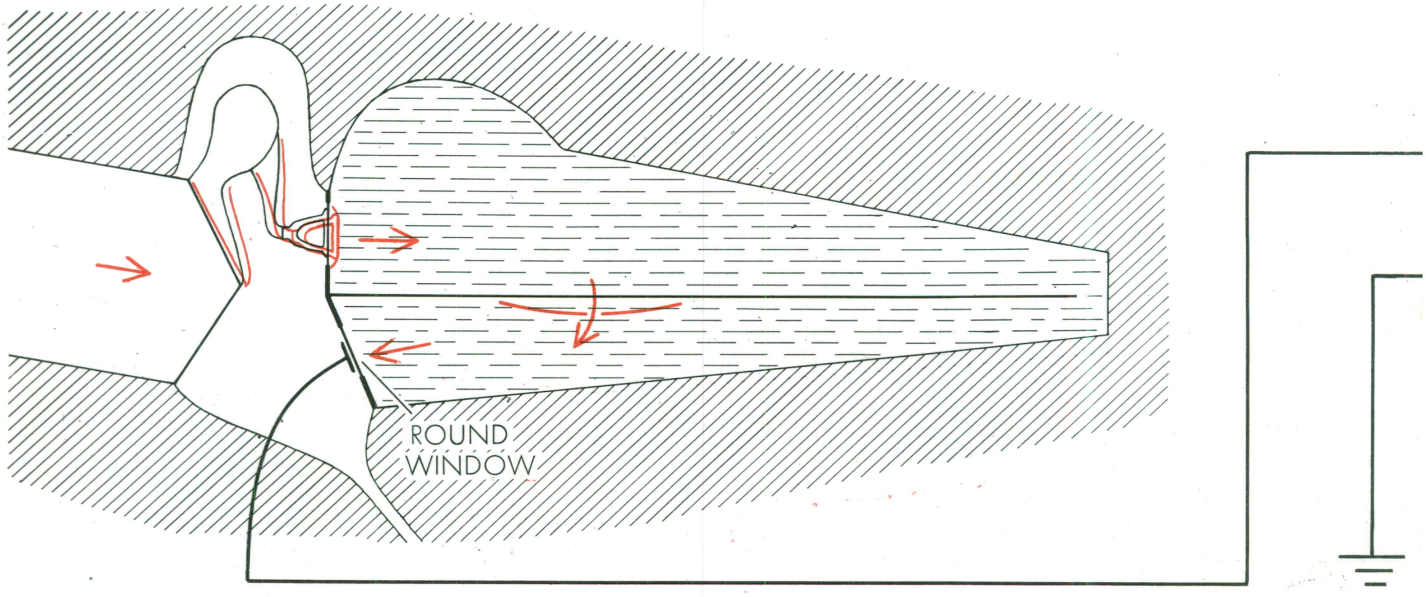
SENSITIVITY OF THE EAR is indicated by this curve, in which the amplitude of the vibrations of the tympanic membrane in fractions of a centimeter is plotted against the frequency of sound impinging on the membrane. Diameter of hydrogen atom is 10^{-8} centimeter.

some of the low-frequency components of the vocal cords' vibrations are lost. This explains why one can hardly recognize his own voice when he listens to a recording of his speech. As we normally hear ourselves, the low-frequency vibrations of our vocal cords, conducted to our own ears by the bones, make our speech sound much more powerful and dynamic than the pure sound waves heard by a second person or through a recording system. Consequently the recording of our voice may strike us as very thin and disappointing. From this point of view we have to admire the astonishing performance of an opera singer. The singer and the audience hear rather different sounds, and it is a miracle to me that they understand each other so well. Perhaps young singers would progress faster if during their training they spent more time studying recordings of their voices.

Feedback to the Voice

The control of speaking and singing involves a complicated feedback system. Just as feedback between the eyes and the muscles guides the hand when it moves to pick up an object, so feedback continually adjusts and corrects the voice as we speak or sing. When we start to sing, the beginning of the sound tells us the pitch, and we immediately adjust the tension of the vocal cords if the pitch is wrong. This feedback requires an exceedingly elaborate and rapid mechanism. How it works is not yet entirely understood. But it is small wonder that it takes a child years to learn to speak, or that it is almost impossible for an adult to learn to speak a foreign language with the native accents.

Any disturbance in the feedback immediately disturbs the speech. For instance, if, while a person is speaking, his speech is fed back to him with a time delay by means of a microphone and receivers at his ears, his pronunciation and accent will change, and if the delay interval is made long enough, he will find it impossible to speak at all.

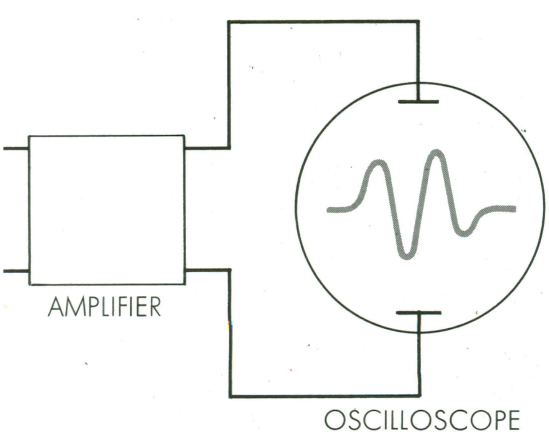


ELECTRICAL POTENTIALS of the microphonic type generated by the inner ear of an experimental animal can be detected by this arrangement. At left is a highly schematic diagram of the ear; the cochlea is represented in cross section by the fluid-filled chamber and the organ of Corti by the horizontal line in this chamber. When the vibrations of the eardrum are transmitted to the organ of Corti,

This phenomenon affords an easy test for exposing pretended deafness. If the subject can continue speaking normally in the face of a delayed feedback through the machine to his ears, we can be sure that he is really deaf.

The same technique can be used to assess the skill of a pianist. A piano player generally adjusts his touch to the acoustics of the room: if the room is very reverberant, so that the music sounds too loud, he uses a lighter touch; if the sound is damped by the walls, he strengthens his touch. We had a number of pianists play in a room where the damping could be varied, and recorded the amplitude of the vibrations of the piano's sounding board while the musicians played various pieces. When they played an easy piece, their adjustment to the acoustics was very clear: as the sound absorption of the room was increased, the pianist played more loudly, and when the damping on the walls was taken away, the pianist's touch became lighter. But when the piece was difficult, many of the pianists concentrated so hard on the problems of the music that they failed to adjust to the feedback of the room. A master musician, however, was not lost to the sound effects. Taking the technical difficulties of the music in stride, he was able to adjust the sound level to the damping of the room with the same accuracy as for an easy piece. Our rating of the pianists by this test closely matched their reputation among musical experts.

In connection with room acoustics, I should like to mention one of the ear's most amazing performances. How is it that we can locate a speaker, even without seeing him, in a bare-walled room where reflections of his voice come at us from every side? This is an almost unbelievable performance by the ear. It is as if, looking into a room completely lined with mirrors, we saw only the real figure and none of the hundreds of reflected images. The eye cannot suppress the reflections, but the ear can. The ear is able to ignore all the sounds except the first that strikes it. It has a built-in inhibitory mechanism.



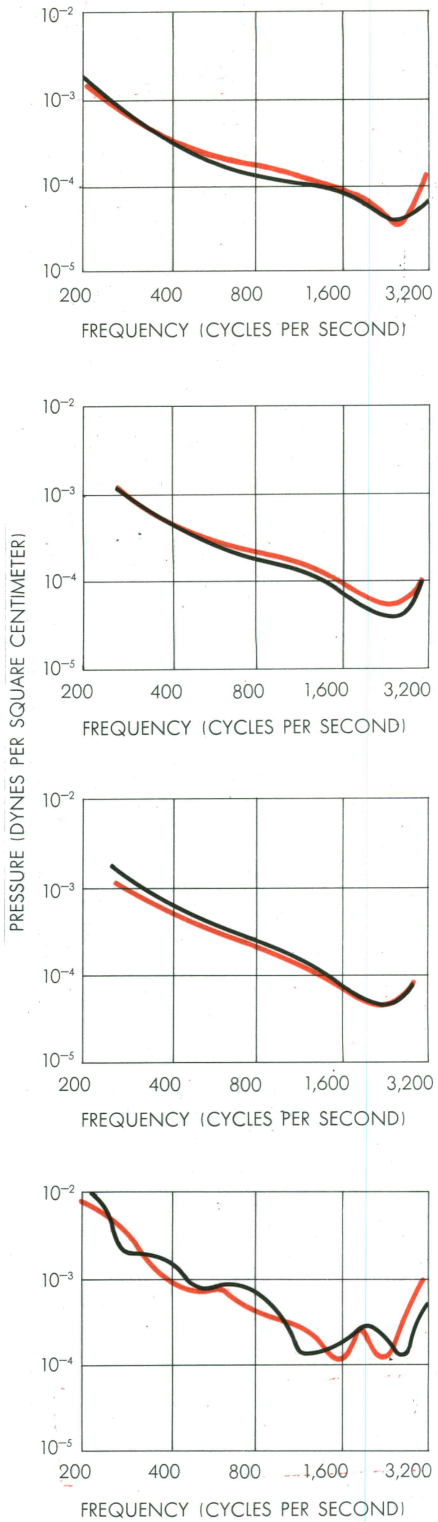
its microphonic potentials can be picked up at the round window of the cochlea and dis-

Suppressed Sounds

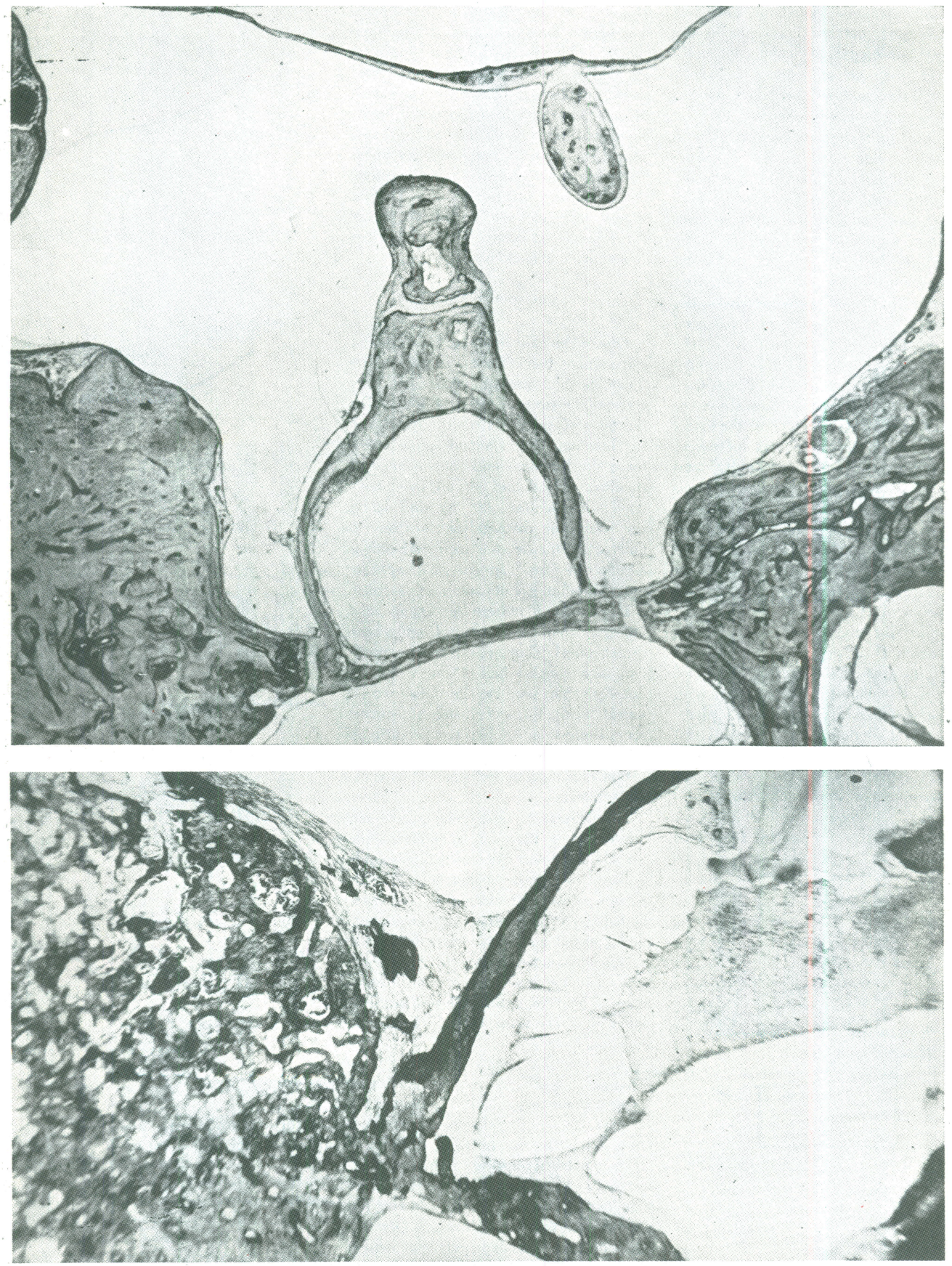
One of the most important factors that subordinate the reflected sounds is the delay in their arrival; necessarily they come to the ear only after the sound that has traveled directly from the speaker to the listener. The reflected sounds reinforce the loudness and tone volume of the direct sound, and perhaps even modify its localization, but by and large, they are not distinguishable from it. Only when the delay is appreciable does a reflected sound appear as a separate unit—an echo. Echoes often are heard in a large church, where reflections may lag more than half a second behind the direct sound. They are apt to be a problem in a concert hall. Dead walls are not desirable, because the music would sound weak. For every size of concert room there is an optimal compromise on wall reflectivity which will give amplification to the music but prevent disturbing echoes.

In addition to time delay, there are other factors that act to inhibit some sounds and favor others. Strong sounds generally suppress weaker ones. Sounds in which we are interested take precedence over those that concern us less, as I pointed out in the examples of the speaker in a noisy room and the orchestra conductor detecting an errant instrument. This brings us to the intimate collaboration between the ear and the nervous system.

Any stimulation of the ear (*e.g.*, any change in pressure) is translated into electrical messages to the brain via the nerves. We can therefore draw information about the ear from an analysis of these electrical impulses, now made possible by electronic instruments. There are two principal types of electric potential that carry the messages. One is a continuous, wavelike potential which has been given the name microphonic. In experimental animals such as guinea pigs and cats the microphonics are large enough to be easily measured (they



AUDIOGRAMS plot the threshold of hearing (in terms of pressure on the tympanic membrane) against the frequency of sound. The first three audiograms show the threshold for three members of the same family; the fourth, the threshold for an unrelated person. The black curves represent the threshold for one ear of the subject; the colored curves, for the other ear of the same subject. The audiogram curves indicate that in normal hearing the threshold in



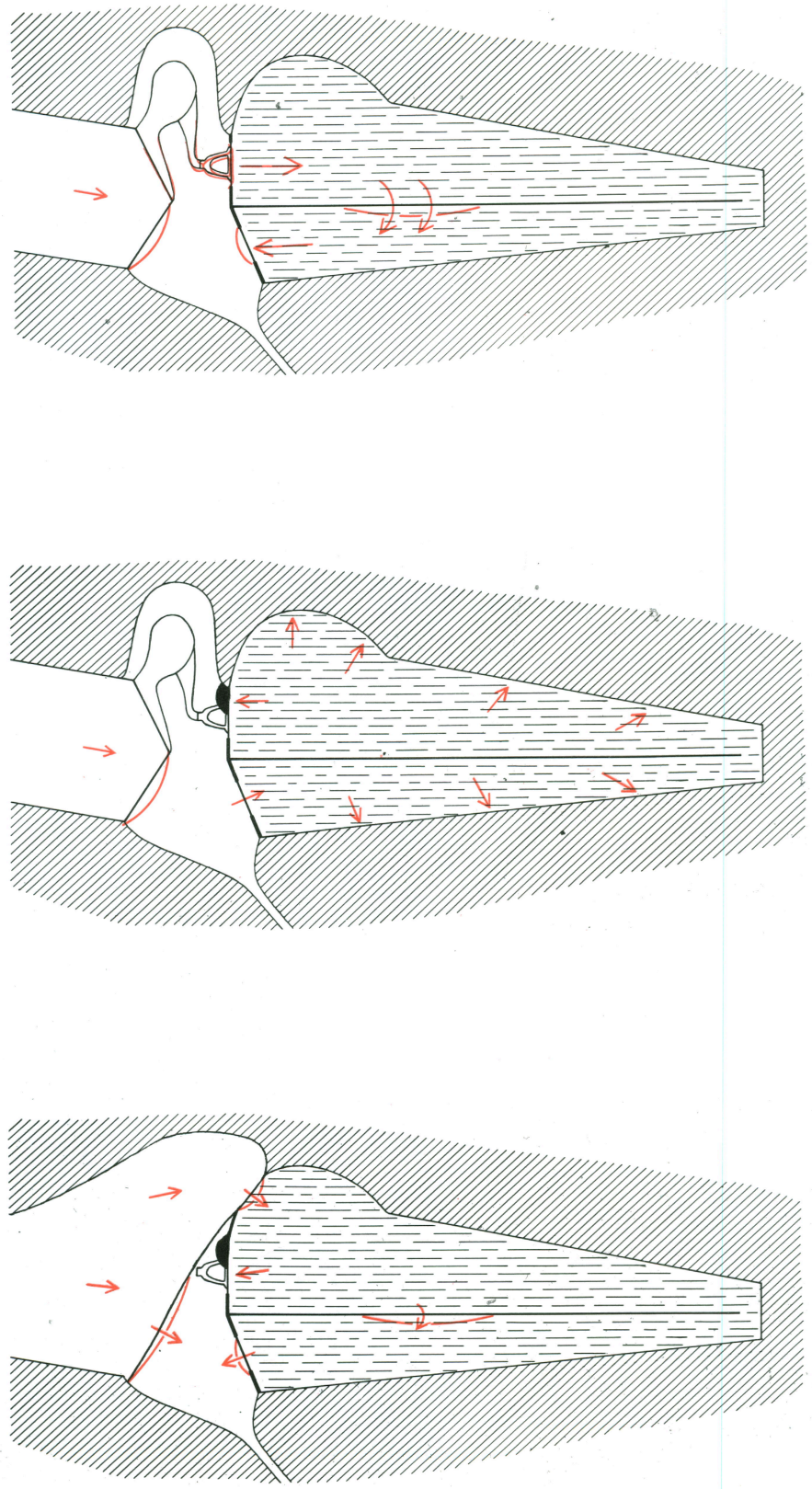
STIRRUP of the normal human ear is enlarged 19 times in the photograph at the top of this page. The thin line at the top of the photograph is the tympanic membrane seen in cross section. The hammer and anvil do not appear. The narrow membrane around the footplate of the stirrup may be seen as a translucent area between the footplate and the surrounding bone. The photograph at the bottom shows the immobilized footplate of an otosclerotic ear. In this photograph only the left side of the stirrup appears; the footplate is the dark area at the bottom center. The membrane around the footplate has been converted into a rigid bony growth.

has turned out that the magnitude of the microphonics produced in the inner ear is directly proportional to the displacements of the stirrup footplate that set the fluid in the inner ear in motion. The microphonics therefore permit us to determine directly to what extent the sound pressure applied to the eardrum is transmitted to the inner ear, and they have become one of the most useful tools for exploring sound transmission in the middle ear. For instance, there used to be endless discussion of the simple question: Just how much does perforation of the eardrum affect hearing? The question has now been answered with mathematical precision by experiments on animals. A hole of precisely measured size is drilled in the eardrum, and the amount of hearing loss is determined by the change in the microphonics. This type of observation on cats has shown that a perforation about one millimeter in diameter destroys hearing at the frequencies below 100 cycles per second but causes almost no impairment of hearing in the range of frequencies above 1,000 cycles per second. From studies of the physical properties of the human ear we can judge that the findings on animals apply fairly closely to man also.

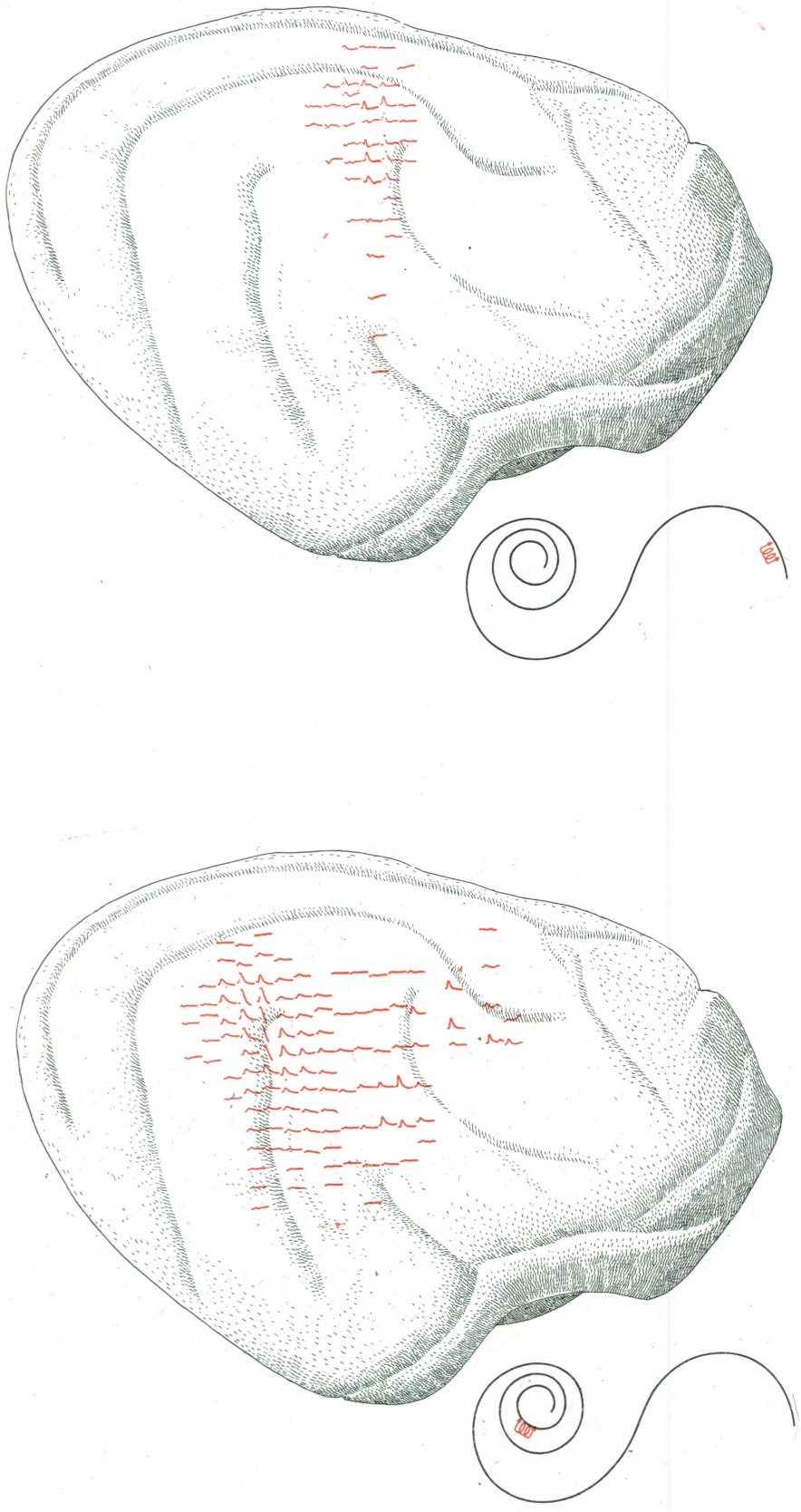
The second type of electric potential takes the form of sharp pulses, which appear as spikes in the recording instrument. The sound of a sharp click produces a series of brief spikes; a pure tone generates volleys of spikes, generally in the rhythm of the period of the tone. We can follow the spikes along the nerve pathways all the way from the inner ear up to the cortex of the brain. And when we do, we find that stimulation of specific spots on the membrane of the inner ear seems to be projected to corresponding spots in the auditory area of the cortex. This is reminiscent of the projection of images on the retina of the eye to the visual area of the brain. But in the case of the ear the situation must be more complex, because there are nerve branches leading to the opposite ear and there seem to be several auditory projection areas on the surface of the brain. At the moment research is going on to find out how the secondary areas function and what their purpose is.

Detecting Pitch

The orderly projection of the sensitive area of the inner ear onto the higher brain levels is probably connected with the resolution of pitch. The ear itself can analyze sounds and separate one tone from another. There are limits to this



FENESTRATION OPERATION can alleviate the effects of otosclerosis. The drawing at the top schematically depicts the normal human ear as described in the caption for the illustration on page 6 and 7. The pressure on the components of the ear is indicated by the colored arrows. The drawing in the middle shows an otosclerotic ear; the otosclerotic growth is represented as a black protuberance. Because the stirrup cannot move, the pressure on the tympanic membrane is transmitted to the organ of Corti only through the round window of the cochlea; and because the fluid in the cochlea is incompressible, the organ of Corti cannot vibrate. The drawing at the bottom shows how the fenestration operation makes a new window into the cochlea to permit the organ of Corti to vibrate freely.



NERVE IMPULSES due to the electrical stimulation of the organ of Corti were localized on the surface of the brain of a cat. The spirals below each of these drawings of a cat's brain represent the full length of the organ of Corti. The pairs of colored arrows on each spiral indicate the point at which the organ was stimulated. The colored peaks superimposed on the brains represent the electrical potentials detected by an electrode placed at that point.

ability, but if the frequencies of the tones presented are not too close together, they are discriminated pretty well. Long ago this raised the question: How is the ear able to discriminate the pitch of a tone? Many theories have been argued, but only within the last decade has it been possible to plan pertinent experiments.

In the low-frequency range up to 60 cycles per second the vibration of the basilar membrane produces in the auditory nerve volleys of electric spikes synchronous with the rhythm of the sound. As the sound pressure increases, the number of spikes packed into each period increases. Thus two variables are transmitted to the cortex: (1) the number of spikes and (2) their rhythm. These two variables alone convey the loudness and the pitch of the sound.

Above 60 cycles per second a new phenomenon comes in. The basilar membrane now begins to vibrate unequally over its area: each tone produces a maximal vibration in a different area of the membrane. Gradually this selectivity takes over the determination of pitch, for the rhythm of the spikes, which indicates the pitch at low frequencies, becomes irregular at the higher ones. Above 4,000 cycles per second pitch is determined entirely by the location of the maximal vibration amplitude along the basilar membrane. Apparently there is an inhibitory mechanism which suppresses the weaker stimuli and thus sharpens considerably the sensation around the maximum. This type of inhibition can also operate in sense organs such as the skin and the eye. In order to see sharply we need not only a sharp image of the object on the retina but also an inhibitory system to suppress stray light entering the eye. Otherwise we would see the object surrounded by a halo. The ear is much the same. Without inhibitory effects a tone would sound like a noise of a certain pitch but not like a pure tone.

We can sum up by saying that the basilar membrane makes a rough, mechanical frequency analysis, and the auditory nervous system sharpens the analysis in some manner not yet understood. It is a part of the general functioning of the higher nerve centers, and it will be understood only when we know more about the functioning of these centers. If the answer is found for the ear, it will probably apply to the other sense organs as well.

Deafness

Now let us run briefly over some of

the types of hearing disorders, which have become much more understandable as a result of recent experimental researches.

Infections of the ear used to be responsible for the overwhelming majority of the cases of deafness. Ten years ago in a large city hospital there was a death almost every day from such infections. Thanks to antibiotics, they can now be arrested, and, if treated in time, an ear infection is seldom either fatal or destructive of hearing, though occasionally an operation is necessary to scoop out the diseased part of the mastoid bone.

The two other principal types of deafness are those caused by destruction of the auditory nerves and by otosclerosis (a tumorous bone growth). Nerve deafness cannot be cured: no drug or mechanical manipulation or operation can restore the victim's hearing. But the impairment of hearing caused by otosclerosis can usually be repaired, at least in part.

Otosclerosis is an abnormal but painless growth in a temporal bone (*i.e.*, at the side of the skull, near the middle ear). If it does not invade a part of the ear that participates in the transmission of sound, no harm is done to the hearing. But if the growth happens to involve the stirrup footplate, it will reduce or even completely freeze the footplate's ability to make its piston-like movements; the vibrations of the eardrum then can no longer be transmitted to the inner ear. An otosclerotic growth can occur at any age, may slow down for many years, and may suddenly start up again. It is found more often in women than in men and seems to be accelerated by pregnancy.

Immobilization of the stirrup blocks the hearing of air-borne sound but leaves hearing by bone conduction unimpaired. This fact is used for diagnosis. A patient who has lost part of his hearing ability because of otosclerosis does not find noise disturbing to his understanding of speech; in fact, noise may even improve his discrimination of speech. There is an old story about a somewhat deaf English earl (in France it is a count) who trained his servant to beat a drum whenever someone else spoke, so that he could understand the speaker better. The noise of the drum made the speaker raise his voice to the earl's hearing range. For the hard-of-hearing earl the noise of the drum was tolerable, but for other listeners it masked what the speaker was saying, so that the earl enjoyed exclusive rights to his conversation.

Difficulty in hearing air-borne sound can be corrected by a hearing aid. Theoretically it should be possible to compensate almost any amount of such hearing loss, because techniques for amplifying sound are highly developed, particularly now with the help of the transistor. But there is a physiological limit to the amount of pressure amplification that the ear will stand. Heightening of the pressure eventually produces an unpleasant tickling sensation through its effect on skin tissue in the middle ear. The sensation can be avoided by using a bone-conduction earphone, pressed firmly against the surface of the skull, but this constant pressure is unpleasant to many people.

Operations

As is widely known, there are now operations (*e.g.*, "fenestration") which can cure otosclerotic deafness. In the 19th century physicians realized that if they could somehow dislodge or loosen the immobilized stirrup footplate, they might restore hearing. Experimenters in France found that they could sometimes free the footplate sufficiently merely by pressing a blunt needle against the right spot on the stirrup. Although it works only occasionally, the procedure seems so simple that it has recently had a revival of popularity in the U. S. If the maneuver is successful (and I am told that 30 per cent of these operations are) the hearing improves immediately. But unfortunately the surgeon cannot get a clear look at the scene of the operation and must apply the pushing force at random. This makes the operation something of a gamble, and the patient's hearing may not only fail to be improved but may even be reduced. Moreover, the operation is bound to be ineffectual when a large portion of the footplate is fixed. There are other important objections to the operation. After all, it involves the breaking of bone, to free the adhering part of the stirrup. I do not think that bone-breaking can be improved to a standard procedure. In any case, precision cutting seems to me always superior to breaking, in surgery as in mechanics. This brings us to the operation called fenestration.

For many decades it has been known that drilling a small opening, even the size of a pinhead, in the bony wall of the inner ear on the footplate side can produce a remarkable improvement in hearing. The reason, now well understood, is quite simple. If a hole is made in the bone and then covered again with a flexible membrane, movements of the fluid in, for instance, the lateral canal of the vestibular organ can be transmitted to the fluid of the inner ear, and so vibrations are once again communicable from the middle to the inner ear. In the typical present fenestration operation the surgeon bores a small hole in the canal wall with a dental drill and then covers the hole with a flap of skin. The operation today is a straightforward surgical procedure, and all its steps are under accurate control.

Hazards to Hearing

I want to conclude by mentioning the problem of nerve deafness. Many cases of nerve deafness are produced by intense noise, especially noise with high-frequency components. Since there is no cure, it behooves us to look out for such exposures. Nerve deafness creeps up on us slowly, and we are not as careful as we should be to avoid exposure to intense noise. We should also be more vigilant about other hazards capable of producing nerve deafness, notably certain drugs and certain diseases.

We could do much to ameliorate the tragedy of deafness if we changed some of our attitudes toward it. Blindness evokes our instant sympathy, and we go out of our way to help the blind person. But deafness often goes unrecognized. If a deaf person misunderstands what we say, we are apt to attribute it to lack of intelligence instead of to faulty hearing. Very few people have the patience to help the deafened. To a deaf man the outside world appears unfriendly. He tries to hide his deafness, and this only brings on more problems.

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